



Geostationary Operational Environmental Satellite (GOES) Space Weather Anomalies

**John Fiorello
The Aerospace Corporation**

This material is being presented to satellite anomaly mitigation stakeholders at the NOAA National Geophysical Data Center and Space Weather Prediction Center Satellite Anomaly Mitigation Stakeholders meeting in Boulder, CO on April 23, 2012. This material is intended for public release



Introduction

The GOES satellite program has been a critical element of the National Weather Service operation since 1975, providing a continuous and reliable stream of terrestrial and near-Earth space environmental data for real-time operational weather forecasting.

GOES 1 through 7 (1975 – 1996) were of a relatively simple design and equally simple to operate. These spacecraft were passively spin-stabilized (@ 100 rpm). The continuous rotisserie mode of the satellite resulted in An effective equal diurnal distribution of the in situ space environment effects on satellite surfaces and components.



Reprinted courtesy of NOAA

The advent of the actively controlled three-axis stabilized GOES-I/M series in April 1994 brought about a revolutionary change in complexity, both in satellite operations and maintainability and in the flight hardware performance in the local geostationary space environment.



Reprinted courtesy of NOAA

This change triggered a new paradigm in the GOES operations world, especially in the area of anomaly detection and correction. The following charts discuss the anomaly process born out of this paradigm and the lessons learned from subsequent anomaly experiences, focusing on those induced by space environment effects.





GOES Anomaly Process

- The aim of the current GOES anomaly process is to protect the health of flight hardware so that it functions and performs throughout mission life and beyond, and to maintain the reliability of the continuous flow of science data
- There are five guiding principles in this process:
 1. **Prevention**: Spacecraft and instruments are designed, built, and tested to ensure they attain mission objectives and meet expected space environment exposure requirements. Analysis of the design identifies potential failure modes that are assigned a severity category based on mission criticality, and single points of potential failure used to evaluate redundancy paths.
 2. **Detection**: Whenever possible, early warning of threatening conditions presents time to react to ensure that there is no unrecoverable damage or degradation that precludes continuation of service. Onboard autonomous Fault Detection and Correction (FD&C) software enhances early warning and reaction to anomaly onset.





GOES Anomaly Process (continued)

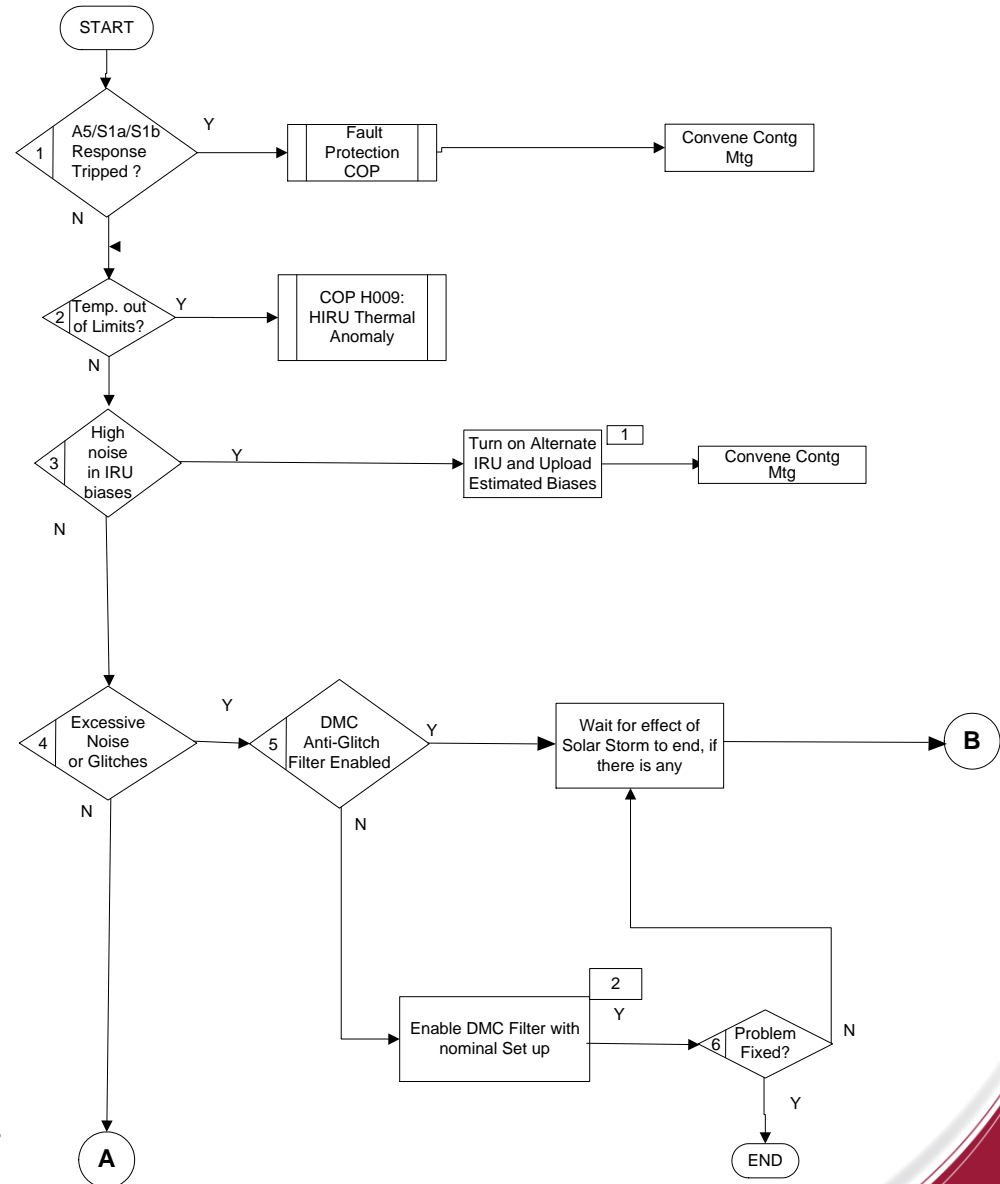


3. **Response:** Anomaly responses are deterministic and associated with specific triggers that are sent to the ground and alarmed. Satellite operators use procedures that provide the logical steps and decision points that lead to safing the affected flight hardware. Objectives of these response sequences are:

First – Avoid service disruption through corrective action (for example, power cycling or redundant side swapping) at the component or box level

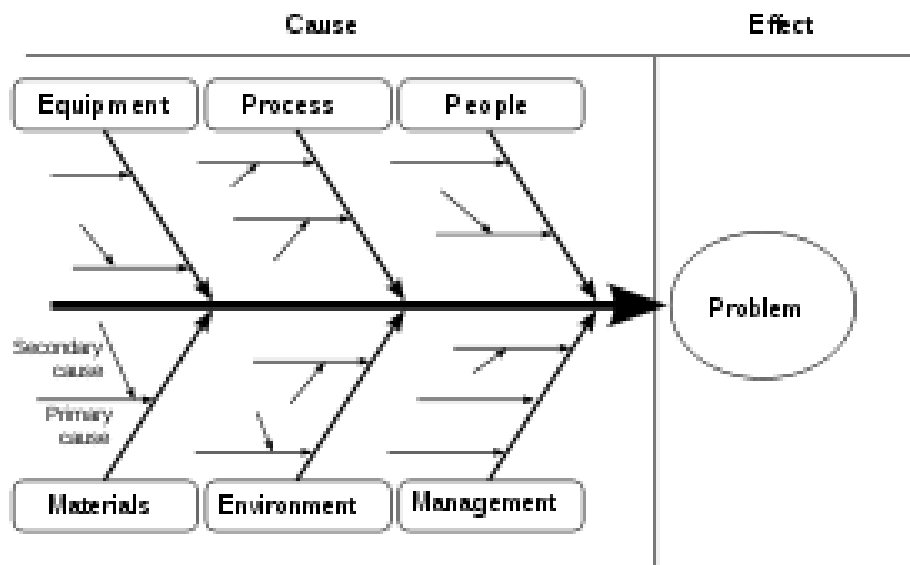
Second – If that is not possible, preserve spacecraft pointing for ground contact Through corrective actions that notify the ground of a more severe response which likely has changed the operational state

Third – If that is not possible, take action To attain a state that is indefinitely safe for power, thermal, momentum, and ground contact standpoint that permits ground engineering expertise intervention.



GOES Anomaly Process (continued)

4. **Investigation**: A systematic cause and effect analysis approach identifies the rank, or rules out, potential root causes based upon correlation with the symptoms and data. An Ishikawa diagram facilitates this analysis. Sometimes (but not always), a single root cause can be identified, with the help of additional diagnostic data or through identifying the necessary and sufficient conditions that distinguish or rank each open root cause. Space weather sensor data provides supporting data to rank and identify root causes on the environment branch.



5. **Correction**: If the root cause of the anomaly is uniquely identified, viable corrective actions are explored. These mostly involve reprogramming flight software or changes in operations that avoid configurations and conditions that aggravate the susceptibility to an anomaly.



GOES Anomaly Process Evolution

These principles have evolved and improved since initiation on GOES-8 as satellite technologies have advanced and as lessons learned have occurred in flying three-axis stabilized GOES satellites in the geostationary space environment:

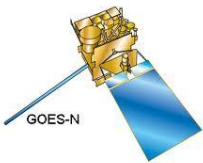
GOES 8 - 12 (1994 – 2011)



Reprinted
courtesy of NOAA

- Inadequate shielding and vague space environment exposure requirements contributed to several GOES-8 anomalies likely caused by radiation and excessive charge accumulation. Additional shielding was added on GOES 9 – 12 in vulnerable areas; these spacecraft experienced no similar anomalies.
- There is no onboard autonomous FD&C flight software. Ground operators are responsible for all anomaly detection and response using the process described on previous charts.

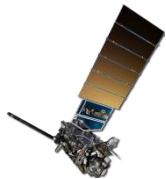
GOES 13 – 15 (1996 – present)



Reprinted
courtesy of NOAA

- Spacecraft and instrument vendors were given in situ space environment exposure requirements for their flight hardware designs.
- The spacecraft onboard computer provides FD&C flight software to autonomously detect and respond to credible single point failures on the spacecraft and, to a lesser extent, the instruments that can permanently preclude operational service. Only spacecraft and instrument engineering data (no science data) is used for anomaly detection, contributing to a GOES-13 anomaly attributed to excessive charge injection during an X-9 solar flare.

GOES-R series (launch readiness in Fall 2015)



Reprinted
courtesy of NOAA

- Spacecraft and instrument vendors were given in situ space environment exposure requirements for their flight hardware designs.
- Spacecraft and instrument onboard computers will provide FD&C flight software to autonomously detect and respond to credible single point failures detected in both engineering and science data.





GOES Space Weather Anomaly History

The table below summarizes the most significant GOES anomalies for which space weather phenomena are among the most likely root causes. (Severity: High = significant impact on mission objectives; Moderate = some degradation of mission objectives; Low = no noticeable impact on mission objectives)

Incident Date	Satellite	Description	Severity
April 22, 1994	GOES-8	Onboard flight processor upsets during elliptical transfer orbit resulted in spontaneous thruster actuation causing attitude control disturbances. (Detailed description on following slides)	High
April 18, 1996	GOES-8	Onboard flight processor upsets in geostationary orbit corrupted resulted in unusable regions of RAM used for on-orbit operations reprogramming data.	High
August 4, 2003			
October 20, 2003		(Detailed description on following slides)	
July 8, 2006	GOES-13	Glitches in the measured gyro rates resulted in a minor spacecraft attitude transient. Gyro glitches are a known phenomena attributed to susceptibility to high energy radiation events. The onboard flight software provides a glitch filter that suppresses these sudden glitches from the spacecraft attitude control loop. Calibration of the glitch filter threshold corrected the problem.	Low
October 27, 2006	GOES-13	A hot pixel was detected in one of the GOES-13 star trackers, resulting in the measured star positions that have high residual errors. This phenomena is attributed to damage in the star tracker CCD silicon caused by charged particles, mainly protons. The spacecraft attitude control flight software is tuned to reject star measurements with high residuals. Sufficient additional star measurements are captured to prevent any noticeable degradation in pointing performance.	Low
December 5, 2006	GOES-13	Severe image blooming was observed in the Solar X-Ray Imager (SXI) during an X9 flare, resulting in permanent damage to 8 CCD columns. (Detailed description on following slides)	High





GOES Space Weather Anomaly Description

GOES-8 transfer orbit flight processor upsets --- April 22, 1994

- GOES-I (-8) was launched on April 13, 1994 into a highly elliptical injection orbit (perigee = ~6500 km, apogee = ~49,000 km) with an inclination of ~27°. The satellite was designed and planned to remain in this orbit environment for approximately 2 days at which the first of four planned orbit maneuver thruster burns would raise perigee by ~17,000 km and reduce the orbit inclination to less ~4.5°.
- Approximately 8 minutes into the first thruster burn, the thruster flange temperature was observed to reach its high temperature tolerance, at which time the burn was aborted. The result was little appreciable change in the GOES-I orbit environment.
- An anomaly investigation into the anomalous flange temperature initiated. During this time, GOES-I continued to traverse through regions of the radiation belt for 7 days, longer than it had been designed to survive.
- On April 22, 1994 the flight processor unexpectedly triggered multiple alarms and transients appeared in the gyro data that caused spurious thruster firings for compensation.
- An investigation of this event pointed to electro-static discharge, precipitated by the prolonged period in the injection orbit environment as the only plausible root cause.
 - Space environment monitoring instruments were not turned on until geosynchronous orbit; corrective action resulted in transfer orbit sequence change to activate energetic particle instruments as soon as possible after launch to permit environmental monitoring
 - As a side note, the investigation into the flange temperature anomaly revealed errors in the pre-launch analysis that determined the abort threshold to be lower than it should have been.)





GOES Space Weather Anomaly Description



GOES-8 geosynchronous orbit flight processor upsets --- April 18, 1996 – October 20, 2003

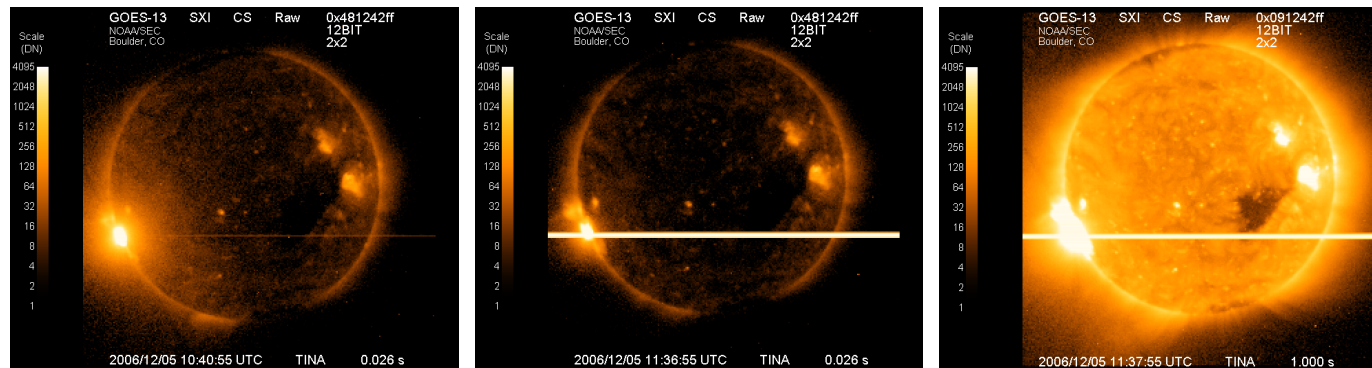
- On April 18, 1996 the primary side flight processor unexpectedly triggered an illegal instruction alarm and disabled the use of reprogrammed software code that was used to correct known performance deficiencies.
- Diagnostic data collected to support the investigation revealed that a large number of contiguous RAM addresses on the chip containing the reprogram code area were corrupted and could not be corrected.
- Although no clear correlation with space weather phenomena was evident, the only plausible root cause explanation for the damaged RAM was an electro-static discharge event.
- Operations engineers switched control to the redundant side flight processor and resumed normal operations.
- GOES-8 was retired from operational service in April 2003. Six months later, the redundant side flight processor experienced similar upsets. Operations engineers returned the satellite to its backup storage configuration until decommission in May 2004.



GOES Space Weather Anomaly Description

GOES-13 SXI image blooming during an X9 flare event --- December 5, 2006

- Initial damage observed at 10:40 UT, and subsequent additional damage increased to 8 CCD columns as imaging continued for over 9 hours until imaging was stopped and the instrument boresight was slewed off of the Sun.



Reprinted courtesy of NOAA

- Imaging continued because the anomaly was not detected in the operations control center
 - All SXI engineering telemetry, exclusively used to detect anomalies, continued to be nominal during this time
 - Solar image displays, usually available in the control center were not available due to an imminent transition move of the operations control center
- These 8 CCD columns are permanently saturated and unusable.
- Failure investigation findings were that radiation from the X9 flare caused localized damage to the CCD array



GOES Space Weather Anomaly Description



GOES-13 SXI image blooming during an X9 flare event --- December 5, 2006
(continued)

- Recommendations for corrective actions were shared:
 - Extensive instrument flight software modifications were made to provide protection from flare induced radiation damage. Detection of flare onset and autonomous switching of observing sequences to use increasingly protective analysis filters as a function of flare intensity was implemented.
 - SXI operations corrective actions were made to develop SXI CCD anomaly detection and response procedures to complement the new flight software changes, to trend accumulated lifetime radiation dose, and to maintain an awareness of the science data through image displays in the control center
 - Science team corrective actions included development of an operational radiation budget based on historical flare data to help define the analysis filter combinations switched to in the flare response sequences that will mitigate CCD radiation damage and provide useful science data at the same time





Summary

The goal of this presentation was to provide insight into the approach to anomalies employed on the GOES satellite development and operations. This is an approach with a conservative foundation based upon a technically simple satellite (GOES 8 – 12) which continues to mature as lessons learned are experienced and as advanced technologies are employed on GOES satellites.

Space weather can be a wavering partner in this approach --- on the one hand providing valuable diagnostic data to corroborate root causes that expose operations or flight hardware vulnerabilities; on the other hand acting as the root cause of space system anomalies.

The space weather anomaly experiences presented demonstrate this approach in action and hopefully can stimulate new ideas on improving the future support of space weather in mitigating and resolving future satellite anomalies

- Thank you

All trademarks, service marks, and trade names are the property of their respective owners

